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14. ABSTRACT

This research program investigated the dynamics of open quantum systems in manifestly quantum or nonclassical domains. The research program exploited recently discovered possibilities in the microscopic realm of quantum mechanics to accomplish tasks that would otherwise be impossible by traditional classical means, including new capabilities for precision measurement and for the processing and distribution of information. Within this setting, the particular investigations related to strong coupling in optical physics whereby nonlinear interactions require only single atoms and photons. The research achieved capabilities beyond traditional nonlinear optics and laser physics and moved into a new regime with dynamical processes involving atoms and photons taken one by one. The research program addressed fundamental issues related to quantum metrology, to quantum communication, and to the general development of quantum information sciences.

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I. SUMMARY OF RESEARCH ACTIVITIES AND ACCOMPLISHMENTS -

The overarching theme of the research program that has been supported by the Office of Naval Research is an investigation of new capabilities for precision measurement and for the processing and distribution of information. The research effort attempted to exploit recently discovered possibilities in the microscopic realm of quantum mechanics to accomplish tasks that would otherwise be impossible by traditional classical means.

Within this setting, the particular investigations that have been pursued related to strong coupling in optical physics whereby nonlinear interactions require only single atoms and photons. In qualitative terms, the research was directed towards advances beyond traditional nonlinear optics and laser physics into a new regime with dynamical processes involving atoms and photons taken one by one. The research program addressed fundamental issues related to quantum metrology as relevant to improved accuracy of atomic clocks, to quantum communication for enhanced channel capacity and secure communication, and to the general development of quantum information science and technology.

The most important accomplishments of this work have been the following.

1. The first demonstration of a laser that operates with a single atom (i.e., the "one-and-the-same atom" laser) [1, 2].

2. The first realization of a deterministic source for single photons that generates single photons "on demand" from one atom trapped in a cavity [3].

3. The development of a protocol for the real-time determination of the number of trapped atoms inside an optical cavity in a regime of strong coupling, with $N = 0, 1, 2, 3 \ldots$ atoms [4].

4. The first experiment to achieve manifestly quantum or nonclassical photon correlations suitable for the implementation of scalable quantum communication networks [5].

Diverse other investigations in the area of Quantum Optics have also been pursued as part of the research program supported by ONR and are described in the accompanying list of publications. A summary of the major aspects of this research is offered in the following sections.

II. A ONE-ATOM LASER IN THE REGIME OF STRONG COUPLING -

Although conventional lasers operate with a large number of intracavity atoms, the lasing properties of a single atom in a resonant cavity have been theoretically investigated extensively in the Quantum Optics community for more than a decade. We utilized the capabilities developed in Ref. [6] for the experimental realization of a one-atom laser operated in a regime of strong coupling [1]. The observed characteristics of the atom-cavity system in this regime are qualitatively different from those of the familiar many atom case. Specifically, we made measurements of intracavity photon number versus pump intensity that exhibited "thresholdless" behavior, and inferred that the output flux from the cavity mode exceeded that from atomic fluorescence by more than tenfold. Observations of the second-order intensity correlation function $g^{(2)}(\tau)$ demonstrated that our one-atom laser generates manifestly quantum (i.e., nonclassical) light that exhibits both photon antibunching $g^{(2)}(0) < g^{(2)}(\tau)$ and sub-Poissonian photon statistics $g^{(2)}(0) < 1$. We also carried out detailed comparisons between our measurements and theoretical models [2].

III. GENERATION OF SINGLE PHOTONS “ON DEMAND” FROM ONE ATOM TRAPPED IN A CAVITY -

A crucial building-block for quantum information science is a deterministic source of single photons that generates one-quantum wavepackets in a well controlled spatiotemporal mode of the electromagnetic field. Moreover, the generation of single photons within the domain of strong coupling in cavity QED enables the reversible transfer of quantum states between atoms and photons, which is a fundamental primitive in protocols for the implementation of distributed quantum networks [7–9]. A single-photon source consisting of a trapped atom strongly coupled to an optical cavity represents an ideal node for such a network, in which internal atomic states can be mapped to quantum states of the electromagnetic field by way of “dark” eigenstates of the atom-cavity system. Converting stationary qubits to flying qubits in this way enables distributed quantum entanglement over long distances by utilizing quantum repeaters.

In Reference [3], we achieved the deterministic generation of single-photon pulses for a single atom strongly coupled to an optical cavity. The photon wavepackets were emitted as a Gaussian beam with temporal profile and repetition rate controlled by external driving fields. Referenced to the total cavity output, the generation efficiency for (un)polarized photons was (0.69 ± 0.10) 0.35 ± 0.05. After correction for detector dark counts, the average suppression of two-photon to single-photon event probabilities was $R_0 = 20.8 \pm 1.8$, rising to $R_0 \gtrsim 150$ at long times, where $R_0 = 1$ for a coherent state. In the absence of passive cavity losses, each generation attempt was inferred to succeed with probability $\phi_G = 1.15 \pm 0.18$. These results represent a major step toward the realization of distributed quantum networks.

IV. CAVITY QED “BY THE NUMBERS” -

We developed a technique for the real-time determination of the number of atoms trapped within the mode of an optical cavity by monitoring the transmission of a weak probe beam [4]. Continuous observation of atom number was accomplished in the strong coupling regime of cavity quantum electrodynamics and functioned in concert with a cooling scheme for radial atomic motion. The probe transmission exhibited sudden steps from one plateau to the next in response to the time evolution of the intracavity atom number, from $N \geq 3$ to $N = 2 \rightarrow 1 \rightarrow 0$ atoms. This is an important advance since many protocols in Quantum Information Science require multiple atoms to be trapped within the same cavity. Experimental efforts to combine ion trap technology with cavity QED are promising, but have not yet reached the regime of strong coupling. In Ref. [4], the atom number was restricted to $N \lesssim 3$, but the novel detection scheme that we developed may enable extensions to moderately larger atom numbers $N \lesssim 10$.

V. THEORETICAL ACTIVITIES -

In addition to this laboratory work, we pursued several theoretical projects. The most significant of these is a scheme for scalable photonic quantum computation based on cavity assisted interaction between single-photon pulses [10]. The prototypical quantum controlled phase-flip gate between two single-photon pulses is achieved by successively reflecting them from an optical cavity with a single-trapped atom. We showed that this protocol is robust to practical noise and experimental imperfections in current cavity-QED setups.

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